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13. ABSTRACT (Maximum 200 words)

The major achievements of this project have been summarized in the Interim Progress Reports. The results of most significance fall in the following major categories. Quasilinear PDEs , the Eikonal Equation, and the Image Irradiance Equation; Photometric Stereo and Interactive Visual Design; Discrete Curvature; Lattice Boltzmann Simulation of Discrete Curvature Flow by Mean Curvature for computer vision and image processing; and Electromagnetic Scattering from Non-Smooth Domains and new Piecewise Polynomial Wavelet Bases

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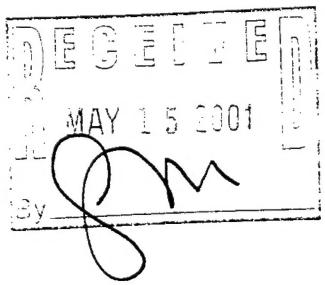

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Dear Mr. Seitz:

Enclosed please find the following reports for the subject award:

Interim Progress Reports for Years 1 through 4 (one of each)
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Thank you for your patience in allowing the University to work out obtaining these reports from Dr. Jawerth. If you have any questions or need any additional information, please call me at (803) 777-7093 or contact me via e-mail at **path@spar.sc.edu.**

Sincerely,

Patricia F Hatcher

Patricia F. Hatcher
Sponsored Program Administrator

Enclosures

cc: R. Stephenson
T. Huggins

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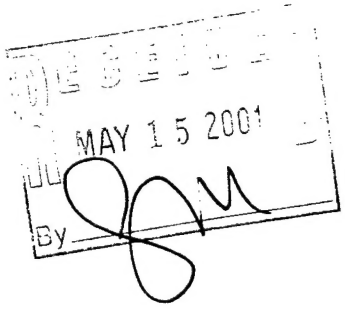

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CONTRACT/GRANT NUMBER: ARO Grant # DAAH04-96-1-036

REPORT TITLE: A FAST PDE SOLVER ENVIRONMENT FOR LARGE-SCALE APPLICATIONS

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SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Björn Jawerth

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

1. **List of Manuscripts:** See separate pages.

2. **Scientific Personnel supported and Honors/Awards/Degrees:**

   Patrik Andersson
   Alexander Andrianov
   Colin Bennett
   Emil Cornea
   Fredrik Ekstedt
   Fausto Espinal
   Stephen Fenner
   Michael Hilton
   Ralph Howard
   Terry Huntsberger
   Björn Jawerth
   Göran Kronquist
   Toshiro Kubota
   Martin Lindberg
   Yiping Mao
   Per Gunnar Martinsson
   Johan Råde
   Henrik Storm
   Sundaram V.
   Weimin Zheng

3. **Report of Inventions: --**
4. **Scientific Progress and Accomplishments:** See separate pages.
5. **Technology transfer: --**

A FAST PDE SOLVER ENVIRONMENT FOR LARGE-SCALE APPLICATIONS

FINAL PROGRESS REPORT

Björn Jawerth

April 28, 2001

U.S. ARMY RESEARCH OFFICE

ARO Grant # DAAH04-96-1-036

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Program directors: Dr. Anna Tsao and Dr. Dennis Healy (DARPA)

A. STATEMENT OF PROBLEM STUDIED

- The objective of this project is to solve Partial Differential Equations associated with descriptions of three-dimensional objects and interactive visual design for manufacturing, design and simulation, and to investigate corresponding computer vision and image processing problems.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

The major achievements of this project have been summarized in the Interim Progress Reports. The results of most significance fall in the following major categories.

- Quasilinear PDEs , the Eikonal Equation, and the Image Irradiance Equation.
- Photometric Stereo and Interactive Visual Design
- Discrete Curvature
- Lattice Boltzmann Simulation of Flow by Mean Curvature for computer vision and image processing
- Electromagnetic Scattering from Non-Smooth Domains and new Piecewise Polynomial Wavelet Bases

For the Eikonal Equation and related first-order nonlinear equations we have obtained a detailed understanding of solutions near singular points. The main results are that there is a strong lack of uniqueness of solutions near such points and that solutions can be less regular than both the function H and the initial data of the problem, but that this loss of regularity only occurs along a pair of curves through the singular point.

For photometric stereo we have focused on reducing the number of photometric images required and on improving the surface integration from the normals. A novel method for surface integration has been developed. It is different then traditional methods, in that it lets the geometry drive the integration path. This method divides the surface into small regions. The surface is integrated over each small path.

The Four Vertex Theorem is a classical theorem involving the extreme points of Euclidean curvature. This theorem was extended by B. Dahlberg (see Interim Progress report Year 1) to cover simple polygons and the appropriate notion of discrete Euclidean curvature. We have generalized this to the affine setting. The correct statement involves a new (discrete) affine curvature. We obtain a discrete six-vertex theorem (generalizing the well-known, classical and nondiscrete setting).

We have studied lattice Boltzmann models for advanced image processing algorithms. The principal advantage of the lattice Boltzmann method over traditional techniques for obtaining solutions of PDEs is that they are naturally well suited for fully parallel machines, resulting in very fast codes. Below we describe several different applications of the lattice Boltzmann model to sonar and image processing.

In recent years nonlinear diffusion has become a powerful tool for intra-region smoothing of images. The results of nonlinear diffusion can be used to obtain an enhanced image or as a precursor to higher-level processing such as image segmentation, shape description, and object detection and tracking. We have developed a lattice Boltzmann model for image filtering by a reaction-diffusion equation. We have tested our methods on various kinds of noisy images including infrared airborne radar images and sonar images. The results are promising.

We have developed a lattice Boltzmann model for mean curvature motion. We have overcome the difficulty of finding a proper collision operator in the lattice Boltzmann equation by using the diffusion generated motion by mean curvature approach.

Based on diffusion generated motion, we have developed a shape recovery system. Our system is capable of recovering shapes of multiple objects, and it automatically changes topology as it searches for the object boundary.

The boundary value problem for the time-harmonic Maxwell equations for a domain in 3D or 2D, can be reduced to solving a layer potential integral equation on the boundary (a surface in 3D or a curve in 2D) of the domain. To study the solutions of these types of equations, we have developed a new class of piecewise polynomial wavelet bases.

C. LIST OF PUBLICATIONS AND TECHNICAL REPORTS

1] E. Cornea, R. Howard, and P-G Martinsson, "The Eikonal and Related First Order Non-linear Partial Differential Equations in Two Independent Variables," preprint.

[2] L. Andersson, R. Howard, and G. Galloway, "A Strong Maximum Principle for Weak Solutions of Quasi-Linear Elliptic Equations with Applications to Lorentzian Geometry", preprint.

[3] L. Andersson, R. Howard, and G. Galloway, "Regularity Properties of the Cosmological Time Function"

[4] L. Andersson and R. Howard, "Rigidity Results for Robertson-Walker Spacetimes"

[5] E.D. Sinzinger and B. Jawerth, "Surface representation from photometric stereo with wavelets", in Proc. SPIE Conf. on Wavelet Applications, Vol. 3169, San Diego, CA, 1997.

[6] B. Jawerth and Y. Mao, "Interactive Visual Design of Surfaces", preprint.

[7] M. L. Hilton and R. T. Ogden. "Data analytic threshold selection in 2D signal de-noising," to appear in *IEEE Transactions on Signal Processing.*

[8] Y. Mao, "Multiresolution analysis and general sampling lattices", preprint.

[9] T. Kubota and T. L. Huntsberger, "Edge dipole and edge field for boundary detection," in *Proc. SPIE Conf. Hybrid Image and Signal Processing VI*, Vol. 3389, Orlando, FL, Apr 1998.

[10] F. Espinal and R. Chandran, "Wavelet-based fractal signature for texture classification," in *Proc. SPIE Conf. on Wavelet Applications V*, Vol. 3391, Orlando, FL, Apr 1998.

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[12] F. Espinal, T. L. Huntsberger, B. Jawerth, and T. Kubota, "Wavelet-based fractal signature analysis for automatic target recognition," *Optical Engineering, Special Section on Advances in Pattern Recognition*, Vol. 37, No. 1, pp. 166-174, 1998.

[13] G. Fernandez and T. L. Huntsberger, "Wavelet-based system for recognition and labeling of polyhedral junctions," *Optical Engineering, Special Section on Advances in Pattern Recognition*, Vol. 37, No. 1, pp. 158-165, 1998.
[14] T. Kubota, T. L. Huntsberger and C. O. Alford, "A vision system with real-time feature extractor and relaxation network," to appear in *Int. Journal Pattern Recognition and Artificial Intelligence*, May 1998.
[15] T. L. Huntsberger and J. Rose, "Computer Simulation of Bimodal Neurons and Networks: Integrating Infrared and Visual Stimuli," chapter in Computer Simulation of Complex Biological Systems, (Ed. I. S. Iyengar), CRC Press, 1998.
[16] T. L. Huntsberger, "Autonomous multirover system for complex planetary retrieval operations," in *Proc. SPIE Symposium on Sensor Fusion and Decentralized Control in Autonomous Robotic Agents*, Vol. 2905, Pittsburgh, PA, Oct 1997, pp. 11-17.
[17] B. Jawerth, P. Lin, and E.D. Sinzinger, "Lattice Boltzmann methods for anisotropic diffusion of images", *Mathematical Imaging*, in review.
[18] K. Debure and T. Kubota, "Autoregressive Texture Segmentation and Synthesis for Wavelet Image On Compression", *10th Image and Multidimensional Digital Signal Processing Workshop*, July 1998, Austria.
[19] S. Godavarthy and T. L. Huntsberger, "Global illumination using Overlapping Wavelets", *Proc. 8th International Conference on Engineering Computer Graphics and Descriptive Geometry* (ICECGDG), Aug 1998, Austin, TX.
[20] E.D. Sinzinger, "Numerical Methods for Ill-Posed Problems in Image Processing and Computer Vision", M.S. Thesis, Department of Computer Science, University of South Carolina, Columbia, SC, 1998.
[21] M. Lindberg, "A new general class of piecewise polynomial wavelet bases", preprint.
[22] B. Jawerth, P. Lin, and E.D. Sinzinger, "Lattice Boltzmann methods for anisotropic diffusion of images", Mathematical Imaging, in review.
[23] H. Karlsson and L. Svensson, "Feature Driven Compression for Curves by Curvature", Master's Thesis, Chalmers University of Technology, Sweden.
[24] E. Cornea, M. Cornea, and B. Jawerth, "Hierarchical Shape Representation and Shape Preserving Approximations, *Wavelet Applications in Signal and Image Processing VI* (A. Laine, M. Unser and A. Aldroubi, eds.),Proceedings of SPIE, vol. 3458, pp.79-91, (1998).
[25] J. Råde, V. Adolfsson, R. Andersson, and B. Johansson, "A Six Vertex Theorem for Polygons", to appear.
[26] E. Cornea, R. Howard, and P.-G. Martinsson, "Solutions Near Singular Points to the Eikonal and Related First Order Non-linear Partial Differential Equations in Two Independent Variables," to appear in *Differential and Integral Equations Journal.*

D. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

Patrik Andersson
Alexander Andrianov
Colin Bennett
Emil Cornea
Fredrik Ekstedt
Fausto Espinal
Stephen Fenner
Michael Hilton
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